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A PROPOSAL TO MEASURE DIRECT PHOTON PRODUCTION AT TEVATRON ENERGIES

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ABSTRACT

We propose to examine the production of direct photons at large transverse momenta in hadron-nucleon collisions at Tevatron energies. We intend to construct a new large-acceptance spectrometer that will enable us to measure with precision the properties of events that contain one or more photons with $p_T \gtrsim 5$ GeV/c. The primary goal of this experiment is obtaining information on quark and gluon interactions through studying the yield of single direct photons and their accompanying hadrons in collisions of π^+, π^- and p with nucleons. In particular, we will determine the gluon structure functions of the pion and the nucleon from rates extracted for the fundamental reactions $qg \rightarrow q\gamma$ (Compton process) and $\bar{q}q \rightarrow g\gamma$ (Annihilation process); we will also measure the fragmentation properties of the gluons and quarks participating in these reactions. We hope, in addition, to extract the signal for the simultaneous production of two primary photons in order to gain information on the $\bar{q}q \rightarrow \gamma\gamma$ process. This elementary reaction, expected to occur at approximately the level of $\bar{q}q \rightarrow \ell^+\ell^-$, offers, in analogy with the Drell-Yan process, a particularly clean test of predictions from QCD.

The experiment is to be performed using 530 GeV/c $\pi^\pm$ and 800 GeV/c proton beams with intensities $\gtrsim 10^7$ per second. Assuming a 25% duty factor for the Tevatron, we require 2000 hours of beam time to complete our investigation; of this, 400 hours will be employed for setup and debugging the apparatus.

I. PHYSICS MOTIVATION

The fundamental nature and underlying importance of direct photon production at large values of transverse momentum would appear to be sufficiently well-established at this time that an extended discussion in each new experimental proposal is no longer appropriate.[1] Indeed, the recent approval at CERN of three such experiments[2] is a rather unambiguous indication of just how great an importance is currently assigned to this type of investigation within the overall high energy physics community. These approvals are all the more noteworthy considering the enormous improvement which can be achieved in such experiments at Tevatron energies (see below).

Briefly summarized, the fundamental importance of the study of direct photon production arises from the elementary nature of the photon and its well-understood electromagnetic coupling. Any hard scattering Feynman diagram that can produce a final state gluon can also produce a photon, albeit with a cross section reduced by the ratio of the electromagnetic and strong coupling constants. By virtue of their elementary nature, however, such photons can emerge as free particles with all the p_T imparted to them in the primary collision, whereas the gluons, in contrast, must fragment into hadrons of generally reduced p_T. Not only does this significantly different behavior serve to enhance the γ/π^o ratio at large p_T, and indeed this ratio is expected to approach unity at the transverse momentum values which we propose to study in this experiment, but even more significantly, and in marked contrast to the situation which prevails for high p_T hadrons, it is not necessary with high p_T photons to first unfold a complicated fragmentation process before getting at the fundamental underlying quark and gluon dynamics.

At large p_T, direct photons are expected to originate mainly from two kinds of hard scattering processes. In p-nucleon and π^+-nucleon collisions the Compton reaction $qg \rightarrow q\gamma$ should dominate, while in π^--nucleon collisions, even at moderate values of x_T (0.3 to 0.6), the annihilation reaction $\bar{q}q \rightarrow g\gamma$ should be just as important.[3] Several of the graphs of interest are illustrated in Fig. 1. The contribution from $gg \to g\gamma$, through a four-quark loop, has been estimated to be negligible.[4] We see that whenever a photon appears in the final state, it must either be accompanied by a gluon, in which case we can study gluon fragmentation, or the scattering had to be initiated by a gluon, in which case we can determine the gluon structure function of the incident hadrons.

An important consequence of the C-invariance of the strong interactions is that the Compton graphs for π^+-nucleon and π^--nucleon collisions are the same, and therefore any difference in the yield of direct photons for these charge conjugate beams can be attributed to the annihilation graph. This point has been emphasized by R. Petronzio[5] and by R. Hagelberg et al[2], and a difference measurement has been proposed for determining the contribution of the annihilation diagram. We plan to take full advantage of this theoretical simplification in the course of our data analysis. (See also the discussion below of target material for further comments.)

The energy of the proton beam for this experiment was chosen to be the maximum expected for normal Tevatron operation. The energies for the pion beams were picked so as to have the same incident momentum per valence constituent as in the case of the proton; this may facilitate comparison of our data with theoretical models.

The only reliable information on direct photon production thus far is from work with proton beams. The bulk of that data is from the ISR[6], where there is now evidence from two groups[7] that the topology of the events at large p_T is consistent with dominance of the Compton graph. Before employing an explicit model for p- and $\pi^\pm$-nucleon collisions at our proposed energies, we first provide an approximate indication of the level of improvement which we can expect to obtain relative to the experiments being presently mounted at CERN.

Figure 2 displays the energy dependence of the π^0 yield measured in pp collisions for some representative p_T values; the curves have each been normalized to the yield at 200 GeV/c. The figure reflects the observed $(1-x_T)^9$ growth with energy of the π^0 invariant cross section at fixed high p_T values. The relevance of these data in the present context arises from the observation made at the ISR that the γ/π^0 ratio at fixed values of p_T is essentially independent of energy. Even though this result is somewhat inconsistent with expectations from simple QCD, it nevertheless provides a convenient phenomenological means for estimating direct photon yields in pp collisions. The figure indicates that, given an energy independent γ/π^0 ratio, dramatic increases in direct photon yields at high p_T values are predicted between 200 GeV/c and Tevatron energies. For example, at p_T = 6 GeV/c the predicted gain is more than 2 orders of magnitude, while at p_T = 7 GeV/c, it is more than 3 orders of magnitude, between an experiment run at 800 GeV/c and one run at 200 GeV/c (such as E629).

For incident pions, the energy variation of the π^0 yield, while expected to be qualitatively similar, need not, of course, be quantitatively identical. To obtain an estimate of what might be expected, we use the results of Fermilab experiment E258 for the reactions $\pi^- p \to \pi^\pm + \ldots$ at 200 and 300 GeV/c.[8] Since in this experiment both the π^+ and π^- yields are observed to vary with energy at fixed p_T in proportion to $(1-x_T)^8$, we infer this same variation for the π^0 yield as well. Figure 3 then displays the thereby predicted growth of the π^0 yield for $\pi^- p$ collisions between 200 GeV/c (the energy of the approved CERN SPS experiments) and 530 GeV/c (the energy of our proposed Tevatron experiment). Quantitatively, the improvement thus predicted is only slightly less dramatic than that measured in the pp case; a factor of $\sim$50 at p_T = 6 GeV/c and of $\sim$250 at

p_T = 7 GeV/c. Viewed in an alternate way, and again assuming an energy independent γ/π^o ratio, at the Tevatron we can expect to observe as many direct photons at p_T^2 = 60 $(GeV/c)^2$ as will be seen at p_T^2 = 35 $(GeV/c)^2$ in the CERN SPS experiments. (This estimate is independent of the anticipated rise of the γ/π^o ratio with increasing p_T; the acceptances of the various experiments are all comparable.) In our proposed experiment, we expect to sample direct photon production up to p_T^2 values of $\sim$100 $(GeV/c)^2$. This is a very significant improvement over even the most optimistic expectations for the lower energy experiments since a factor of just 2 or 3 in Q^2, while nominally affecting α_s only slightly ($\sim$10%), can provide for a far cleaner test of QCD phenomenology.[9] Furthermore, the experiments which have recently been approved to run at the CERN SPS will lack the fine-grained, high resolution, photon detection capability so essential for an optimum experiment of this type.[2]

In addition to investigating the dynamics of single photon production at high p_T, we also wish to extract the signal for the production of two direct photons. The two leading contributions are depicted in Figure 4. The yield for this process is expected to be comparable to that for Drell-Yan annihilation into lepton pairs. In contrast to the case of single γ production, the contribution of $gg \rightarrow \gamma\gamma$ may here be comparable to that from $\bar{q}q \rightarrow \gamma\gamma$.[10] Once again the π^+/π^- comparison can be used to extract the contribution from the annihilation process. Roughly speaking, the contribution of this process to the two γ cross section can be expected to be about $\alpha/\alpha_s \sim (1/137)/(1/4) \sim 1/35$ of the contribution of the reaction $\bar{q}q \rightarrow g\gamma$ to the single γ cross section. Consequently, exclusive of any contribution from the $gg \rightarrow \gamma\gamma$ diagram[11], the rate for the two photon process in π^--nucleon collisions can be expected to be approximately 1/70 of that for the production of a single γ. Taken literally, this would imply that an experiment which is designed to measure single photons up to p_T values of $\sim$10 GeV/c should also be able to investigate the two photon continuum up to masses of $\sim$16 GeV/c, corresponding to two photons with approximately equal, but opposing, values of $p_T \approx 8$ GeV/c. (This estimate assumes a variation of the invariant cross section for single γ production with p_T in proportion to $(1-x_T)^8/p_T{}^8$, in agreement with the measured rate for $\pi^{\pm}$ production at 200 and 300 GeV/c; it is not intended to be more than a rough approximation to reality.)

Our interest in the two photon process stems not only from the fact that it can provide an important source of information concerning the gluon distribution in hadrons, but also because the process $\bar{q}q \to \gamma\gamma$ is a fundamental interaction, akin to the Drell-Yan process (see Fig. 4). If higher order QCD corrections for the two reactions differ, then it is especially important to check whether the same discrepancy (by a factor of $\sim$2.4) between theory and experiment will be found in the $\gamma\gamma$ case as has been uncovered in the Drell-Yan case. This might provide a very significant test of the reliability of the perturbative QCD approach to the study of strong interactions.(12)

The preceeding estimates are only intended to provide a rough guide to the overall sensitivity of our proposed experiment. More detailed, and more model dependent, estimates of yield will be presented below. We also wish to observe that we will of necessity also collect data containing multiphoton events. These data will permit us to search for possible high mass narrow states in relatively unexplored channels such as $\pi^0\gamma$, $\eta^0\gamma$, $\pi^0\eta^0$, etc. Despite the potential for exciting surprises, we choose not to emphasize this aspect of the proposal in arguing for its approval.

Finally, it is appropriate to mention the kind of competition we can expect from the ISR and the CERN $\bar{p}p$ collider over the next several years. There is, of course, substantial overlap in the types of problems which can be challenged. In particular, gluon fragmentation and the annihilation process $\bar{q}q \rightarrow g\gamma$ can be studied very well with $\bar{p}p$ interactions. However, the anticipated relative loss of a factor of $\sim$20 in luminosity (even at the low- regions of the colliders) and difficulties of geometry will make these experiments exceptionally difficult. We believe that our proposal will be certainly competitive with any such experiment which might be envisioned at the ISR. Interactions at the colliders (both CERN and Fermilab), although at comparable p_T, will be in a totally new domain, and we cannot judge their outcome. In any case, however, our data will be mainly at moderate values of x_T ($\sim$.5), while the data from the colliders will be primarily for $x_T \lesssim .05$. In this sense, the two sets of data will be complementary, and a comparison of relative yields should prove to be quite informative.

II. Experimental Arrangement

A. Overview

We had hoped that prior to the preparation of this proposal, we would have available data from our test experiment E629 to assist in refining our ideas. Unfortunately, events beyond our personal control have precluded this possibility. Therefore, we base most of the design aspects of this proposal on "a priori" considerations only slightly modified by the earliest indications from E629. Undoubtedly, and most appropriately, our ideas will be further refined during the months ahead, and some aspects of the experimental arrangement herein described could undergo significant modification before the ultimate experimental design is achieved. Nevertheless, these ideas accurately represent our present conception for the experimental arrangement, and they certainly provide a reliable guide as to our definition of the scope and the scale of our proposed experiment.

Figure 5 summarizes the general features of our proposed spectrometer. We believe that the sensitive area and granularity of our proposed new photon calorimeter will remain basically as described; the specific decisions regarding its detailed design, however, and in particular whether it should utilize liquid argon or some other material, must await the results of E629 as well as tests being performed elsewhere.(13) Notwithstanding the preceeding, however, our present inclination is to build a liquid argon calorimeter of the type to be described below.

The overall acceptance of the spectrometer is another design feature which we anticipate remaining basically unchanged. We envisage a system with an acceptance of essentially 2π in azimuth and of approximately 2 units in rapidity, centered at $y_{cm} = 0$ at 530 GeV/c. The system will span a range of laboratory angles of from 22 mr to 167 mr (corresponding to laboratory pseudo-rapidities ranging from 4.5 to 2.5). We have designed the system to provide sufficient coverage in the forward direction in the center of mass to accomodate the expected forward peaking of the photon yield in π-nucleon interactions.(14) The overall acceptance of our proposed new spectrometer is about a factor of 14 larger than that characterizing the geometry of E629. When this factor is combined with the large increase in yield anticipated in going to 530 GeV/c, we expect in excess of 10^4 events with $p_T \gtrsim 5$ GeV/c per 200 hours of π^- running time (in contrast to only a few dozen using the

E629 spectrometer). To obtain explicit rates, we employ the specific model used by R. Hagelberg et al. to estimate their yields.[15] This model includes contributions from both $\bar{q}q$ annihilation (both valence and sea quarks) and gq Compton scattering (beam and target gluons added incoherently). Scaling violation is included, but not p_T smearing. (See P. Hagelberg et al.[2] for further details concerning the explicit parametrization of the various structure functions, etc..) Table 1 presents the model predictions for stated assumptions concerning the experiment. Background rates, using both Monte Carlo estimations and the results of E629, will be discussed at the time of our oral presentation.

We close this overview with the observation that it could undoubtedly be argued that by ignoring more complicated diagrams which might contribute to the direct photon yield, we are taking an excessively naive view of nature. There is, however, considerable theoretical divergence on this point with some optimists arguing that higher order graphs will not significantly alter the first order phenomenology.[1] Our position is that this simple model, and our earlier extrapolations, should be adequate to indicate the high quality of the data which we can expect to acquire, and to suggest how valuable these data will be in helping confront some of the most interesting present issues in strong interaction dynamics.

B. Components

The major elements of our proposed experimental arrangement are described in more detail below.

1. The Beam

To achieve our experimental goals, we require a beam capable of delivering $\gtrsim 10^7$ π^- per second within a beam spot of $\sim$1 cm^2. The upgraded M1 beam in its second phase would appear to satisfy these requirements, but our proposed π^+ running will pose some additional constraints. With sufficient total flux, selective filtering can be employed to significantly reduce the proton component of the beam[16], but tagging to separate pions and protons will nevertheless be required. This would appear to necessitate a parallel beam section for Cerenkov identification, a feature not presently incorporated into the planned M1 upgrade. An attractive alternative, however, in light of the uniquely high γ values characteristic of pions in this experiment might be a transition radiation detector segmented sufficiently to achieve the necessary rate capability; we are currently investigating this possibility. A somewhat less appealing option would be to obtain our π^+ data via a subtraction technique. This could involve the use of varied levels of filtration along with, possibly, a short run of essentially pure protons (obtained by running the Tevatron at lowered energy). Clearly, any such procedure would greatly complicate both the data collection, and, most significantly, the data analysis of the experiment, and, in consequence, would be employed only as a last resort.

2. Charged Particle Detection

We require a large aperture magnet with a vertical gap of $\sim$40 cm and a field integral of $\sim$1 T•m. In the region in front of the magnet, we plan to install an array of silicon strip detectors.(17) Our present intent is to position 2 such detectors upstream of the target (in an xy orientation), and 5 more immediately downstream of the target (oriented in an incremental sequence of 72° to provide maximum stereoscopic discrimination). Figure 6 displays a sketch of the proposed arrangement; it is not presently certain how close the detectors can be positioned without interference between their readouts. We are currently investigating the pattern recognition difficulties introduced into the software by the proposed downstream chamber configuration. We propose to construct each silicon detector with a center-to-center strip separation of $\lesssim$100 μm. This very fine spatial resolution will provide us with an excellent capability for resolving charged track reconstruction ambiguities, and for determining the interaction vertex and the magnet entrance angle for each secondary track. We anticipate that these devices will not be sufficiently damaged by exposure to radiation during our data taking to necessitate replacement of the silicon wafers.[18]

Downstream of the magnet we will rely on conventional PWC planes. We plan to employ 3 independent sets of planes, each capable of generating space points (each set to consist of 2 orthogonal pairs at 45° relative to one another). These chambers will span the beam, and will therefore require desensitized central regions. Our present idea is to achieve this requisite deadening by negatively biasing the sense wires in the regions in question so as to drive the chambers locally below sensitivity. The presence of 4 chambers in each set will provide the potential for at least 3 hits for all but the central region. The overall redundancy will be further enhanced by rotating each of the 3 sets by 15° relative to the others; this will provide the potential for 4 hits in at least 2 chamber sets for each charged secondary (outside of the beam region in which it is our intent to deaden the system). Figure 7 displays a sketch of the proposed chamber configuration indicating the orientation angle for each chamber, and detailing the central region for a set of 4 chambers. We anticipate that the high degree of redundancy provided by our proposed chamber configuration will be essential in disentangling high multiplicity events. We estimate a momentum resolution of $\lesssim 5\%$ for charged secondaries of up to 100 GeV/c; we will refine this estimate by the time of our oral presentation. Finally, although not specifically addressed in this proposal, we certainly recognize the intrinsic value of secondary particle identification. The spacing of the downstream PWC's can be easily altered to permit the installation of an imaging Cerenkov counter as part of a future upgrade of our proposed apparatus (at the cost of introducing additional material upstream of the photon detector).

3. Photon Detection

As previously stated, we presently favor the construction of a liquid argon calorimeter. We have acquired extensive experience with this proven technique, and believe that even a factor of two or three reduction in response time which might be gained through the use of an alternate technology would be outweighed by the excellent linearity, long term stability, and, quite possibly, lower cost of a liquid argon system. We envisage a detector similar in conception to the one employed in E272 and E629, but possessing cylindrical symmetry. Our present plans call for an active area of 1.5 m outer radius with a beam hole of 20 cm radius, and for the entire detector to be installed in a single cylindrical dewar of $\sim$2 m radius. While we would prefer to build a system which can be evacuated, detailed engineering studies will be required before a firm decision on this issue can be reached. The question of access to the inside of the dewar is similarly complex. While access through just the top will not present us with any new problems relative to those already solved in constructing our present device, it is not clear whether it is technically and economically feasible to equip the dewar with a removable back cover (which would considerably simplify the assembly of the inside detector). In any event, the overall size of the proposed device will clearly be consiberable, and necessitate the construction of a special pit if the experiment is to be installed in the Meson Lab. (Fortunately, there is precedence in this experimental area for such an architectural modification.)

In keeping with the choice of cylindrical geometry, we plan to employ an (r,ϕ) readout. This will involve the use of g-10 boards with concentric circular strips to measure the radial energy deposition, interleaved with boards etched with radially directed strips to measure the azimuthal variation. The circular strips will be 5 mm in width, and the locations of the strip centers will be gradually fanned out as one goes deeper into the detector in such a way as to focus the detector on the target. There will be 260 circular strips on each board. It is our present intent to subdivide the radial strips at the mid-radius of the detector. The inner strips will have a minimum width of $\sim$2 mm and spread out to $\sim$8 mm at their maximum radii of 85 cm; the outer strips (2 for each inner strip) will vary from $\sim$4 mm to $\sim$7 mm in width. (The strip width will be $\sim$5 mm at a distance from beam center corresponding to $y_{cm}=0$ at 530 GeV/c; the natural size of electromagnetic showers does not justify a detector granularity finer than $\sim$5 mm.) This proposed segmentation would result in a total of 664 inner strips, and twice this many outer strips. Readout of the inner strips poses a special design challenge which we are presently addressing. Should a satisfactory solution fail to emerge, we would propose an alternate subdivision of the radial strips into two equal area segments both of which can be read out from their outer edges (see Fig. 8). The detector will be electronically subdivided into independent octants for a total of 4072 (or 3408) channels in its front section. The detector will be subdivided into two sections along the beam direction; the upstream unit will contain 15 radiation lengths of material, while the downstream unit will contain 10. To reduce the total number of amplifier channels required, the downstream section of the detector can be constructed using strip widths twice those of the front section. A sketch of the active area of the proposed detector is presented in Figure 8.

The large size of the photon detector described has been in part dictated by our desire to sample the neutral (π^o) as well as the charged energy accompanying the direct photon. This information will be vital for extracting details of the gluon fragmentation process, one of the major goals of this experiment.

4. Target Selection

The proposed $\pi^+ - \pi^-$ difference measurement for obtaining the contribution of the annihilation diagram is not restricted to the case of nuclear targets. In fact, the difference per nucleon (ignoring $\bar{q}$ contributions from the sea) is a maximum (by a factor of 2) in the case of hydrogen. Nuclear targets do however have the virtue of being compact and easy to handle, and moreover the use of an I=0 target such as carbon has the important added advantage of eliminating any residual π^o and η^o background through the $\pi^+ - \pi^-$ subtraction. We therefore propose to employ a 10% absorption length carbon target for most of our data taking; for comparison purposes, we will replace this with a similar beryllium target for part of the run. We reserve as a future option the installation of a liquid hydrogen target; to achieve the same level of sensitivity, this would necessitate raising the beam intensity by a compensating factor of $\sim$3.

5. Experimental Trigger and Backgrounds

One of the primary goals of our currently running test experiment E629 is the investigation of these two important topics. The E629 trigger involves specially constructed modules which enable us to establish independent triggering thresholds for the total transverse energy deposited in the LAC (global p_T), and for the peak transverse energy deposited in 3 adjacent strips (local p_T). In the limited amount of beam time to which we have had access to date, we have found setting the local p_T threshold to $\sim$1/3 that of the global threshold to be clearly effective in reducing background. Unfortunately, we are not able at this time to be more quantitative; it is certainly our intention to have acquired much more data on the effectiveness of this technique by the time of our oral presentation. It is, however, worth emphasizing that, relative to E629, background rates should be considerably reduced at the higher energies and larger p_T values characterizing this proposed Tevatron experiment. Moreover, the cylindrical geometry chosen for our new LAC will be more ideally suited for the type of global p_T/local p_T fast logic which we are currently investigating in E629.

III. SUMMARY

We propose to investigate the detailed characteristics of events which have direct photons produced at large transverse momenta in hadron-nucleon collisions. At large values of p_T, the photon yield is expected to be comparable to that for π^o and η^o production. The fine-grained photon detector which we propose to construct will provide excellent γ/π^o discrimination. The π^o, η^o and ω^o yields (interesting in their own right) will be measured with precision and used to subtract remnant background from the observed single photon signal. Comparison of the yields for π^+, π^- and p projectiles in a single experiment over a wide range of rapidity will permit us to extract the gluon structure function for these hadrons, and also to analyze the fragmentation properties of quarks and gluons. Data that will be obtained on direct two photon production will provide further information on the gluon content of hadrons, and will also serve as a new and important testing ground for QCD. In addition, the large acceptance and excellent resolution of our proposed spectrometer will enable us to search for possible new massive meson states (glueballs, etc.) produced in hadronic interactions.

The cost of mounting this experiment will be considerable (of the order of \$1M or more); we are presently preparing a more detailed breakdown of the estimated expenses. In addition to those already committed, we expect to add at least one more participating group, possibly from outside the U.S.. This will help spread out the financial burden, and assure the necessary expertise and manpower to successfully complete the proposed program. We anticipate a 2 to 3 year construction schedule for the major components of the apparatus.

We wish to thank J. Badier, A. de Rujula, L. Hubbeling, M. Jacob, T. Ludlam, R. Petronzio, C. Quigg, J. Rosner, L. Stodolsky, and I. Stumer for helpful discussions and encouragement.[19]

FOOTNOTES AND REFERENCES

(1) An excellent summary of the physics possibilities is offered by F. Halzen and D. M. Scott, Madison Report DOE-ER/00881-15G (1980). In remarkably enthusiastic fashion these authors sketch why direct photons is "the way" to do high-p_T physics with hadrons.

(2) L. Bachmann et al., Geneva-Neuchatel Collaboration, CERN/SPSC/80-61 (1980);

A. Bamberger et al., Bari-Freiburg-ITEP Moscow-Max Planck Inst.-Munich-Nijmegen Collaboration, CERN/SPSC/80-83 (1980);

R. Hagelberg et al., CERN-Saclay-Collège de France-Ecole Polytechnique-Orsay-Pisa Collaboration, CERN/SPSC/80-109 (1980).

(3) See Ref. 1 and previous work referred to in that paper. Also, the proposal of R. Hagelberg et al. (Ref. 2) has detailed comparisons of the contributions from the various graphs.

(4) B. L. Combridge, CIT Report CALT-68-766 (1980).

(5) Private communication. We thank Dr. Petronzio for a helpful and encouraging discussion.

(6) See M. Diakonou et al., Phys. Lett. 91B, 296 (1980), and reference to previous work given therein and in our earlier proposal (E629) to Fermilab.

(7) Private communication from W. Molzen from ISR experiment R807, and from L. Camilleri of the CCOR group. See also the latest data and theoretical comments contained in the summary of the CERN Discussion Meetings Between Experimentalists and Theorists on ISR and Collider Physics, Series 2, Number 1 (1980), M. Albrow and M. Jacob,eds.

(8) Private communication from N. Giokaris.

(9) See the remarks of S. Brodsky in his lectures at the 1979 SLAC Summer Institute, SLAC-PUB-2447 (1979), and the work of M. Creutz, Phys. Rev. D21, 2308 (1980).

(10) See Ref. 4 and C. Carimalo et al., Phys. Lett. 98B, 105 (1981). Carimalo et al. stress the importance of the two photon measurement, particularly with regard to the extraction of the gluon structure function of hadrons via the process $gg \rightarrow \gamma\gamma$. See also reference to earlier work given in these two papers.

(11) It is interesting to note that the latest data from the R807 group at the ISR provides an indication for the presence of a two-photon signal in pp collisions. The order of magnitude of the yield is consistent with expectations from antiquarks from the sea. The data are not yet sufficiently refined to shed light on the $gg \rightarrow \gamma\gamma$ question. We thank Dr. I. Stumer of BNL for a valuable discussion of the latest data and phenomenology and for providing us with a copy of E. Paschos' report (early 1970's) on massive photon pairs.

(12) Dr. C. A. Nelson of SUNY Binghamton is presently examining this problem.

(13) We await with interest the results of the development work currently being carried out at the University of Geneva on liquid scintillator detectors by M. Martin and collaborators, and at Fermilab in the M5 test beam on argon gas detectors by R. Walker and collaborators.

(14) The peak of the photon yield is expected to occur between 1/3 and 1/2 rapidity units forward of $y_{cm}=0$. For explicit calculations demonstrating this effect, see R. Hagelberg et al., Ref. 2.

(15) We thank J. Badier for providing us with detailed calculations for our energies. Our use of the Hagelberg et al. model to calculate our yields has the advantage of facilitating comparison between our experiment and theirs. The rates based on this model are similar to those predicted by B. L. Combridge, Ref. 4.

(16) During our 1979 data run for experiment E272, we successfully employed a beryllium filter to enhance the kaon fraction of our 200 GeV/c positive beam without observing significant deterioration in our Cerenkov tagging efficiency. Using 2.2 m of Be, we were able to change the beam composition ($p:\pi^+:K^+$) from (.81:.16:.03) to (.29:.51:.20). For further details, see A. Jonckheere et al., Fermilab report TM-983 (1980) (to be published in Nucl. Instr. and Meth.).

(17) Great progress has recently been made in the development of such detectors at CERN; e.g. the report of E. H. M. Heijne, et al., Nucl. Instr. and Meth. 178, 331 (1980). The CERN-Munich collaboration (B. Hyams et al.) is presently preparing a 1000 channel system for use at high intensities during the 1981 summer SPS running period. Members of our collaboration are also presently actively investigating such detectors at Fermilab.

(18) Current estimates are that such detectors can withstand an integrated flux of 10^{14} charged particles per cm^2. See the report of Ref. 17 and T. Ludlam's summary at the Pisa Conference on the Miniaturization of Detectors (1980) for further details. In any event, the cost of the silicon wafer is expected to be small compared to the cost of the accompanying electronics.

(19) T. Ferbel wishes to especially thank E. Gabathuler, the EP Division at CERN, and the Fabjan-Willis group for their hospitality and support while working on this proposal.

Table 1

Expected Yield of Direct Photons

Number of Events per 1 GeV/c Interval in p_T

p_T	$\pi^- C$		$\pi^+ C$		pC	
(GeV/c)	(500 hrs at 530 GeV/c)		(700 hrs at 530 GeV/c)		(400 hrs at 800 GeV/c)	
	[γ]	[γγ]	[γ]	[γγ]	[γ]	[γγ]
5	34,000	330	34,000	120	29,000	90
6	9,500	90	9,000	40	6,000	20
7	2,500	26	2,100	11	850	3
8	650	8	450	3	160	
9	180	3	120	1	40	
10	50	1	25		7	
11	12		5		1	

The numbers in this table were obtained assuming a 2π azimuthal acceptance and a rapidity coverage of 2 units centered at $y_{cm} = 0$. We assumed 10^7 beam/sec for incident pions, and 1.5×10^7 beam/sec for incident protons. A 10% absorption length target was assumed, and a 25% duty factor for the Tevatron. The columns labeled [γ] are for a single photon in the indicated p_T range; the columns labeled [γγ] are for two photons in our range of acceptance and at least one within the given p_T range.

FIGURE CAPTIONS

1. Elementary diagrams contributing to the direct photon signal in hadronic collisions. (Permutations and exchange graphs for the indicated processes are not explicitly shown.)

2. Measured energy dependence for π^o production in pp collisions for representative values of p_T. Curves are normalized to the yield at 200 GeV/c.

3. Transverse momentum dependence of the relative yield of π^o mesons in $\pi^- p$ collisions. The increase of the π^o yield between 200 GeV/c and 530 GeV/c has been estimated using an extrapolation from measured $\pi^{\pm}$ data; see text for explicit details.

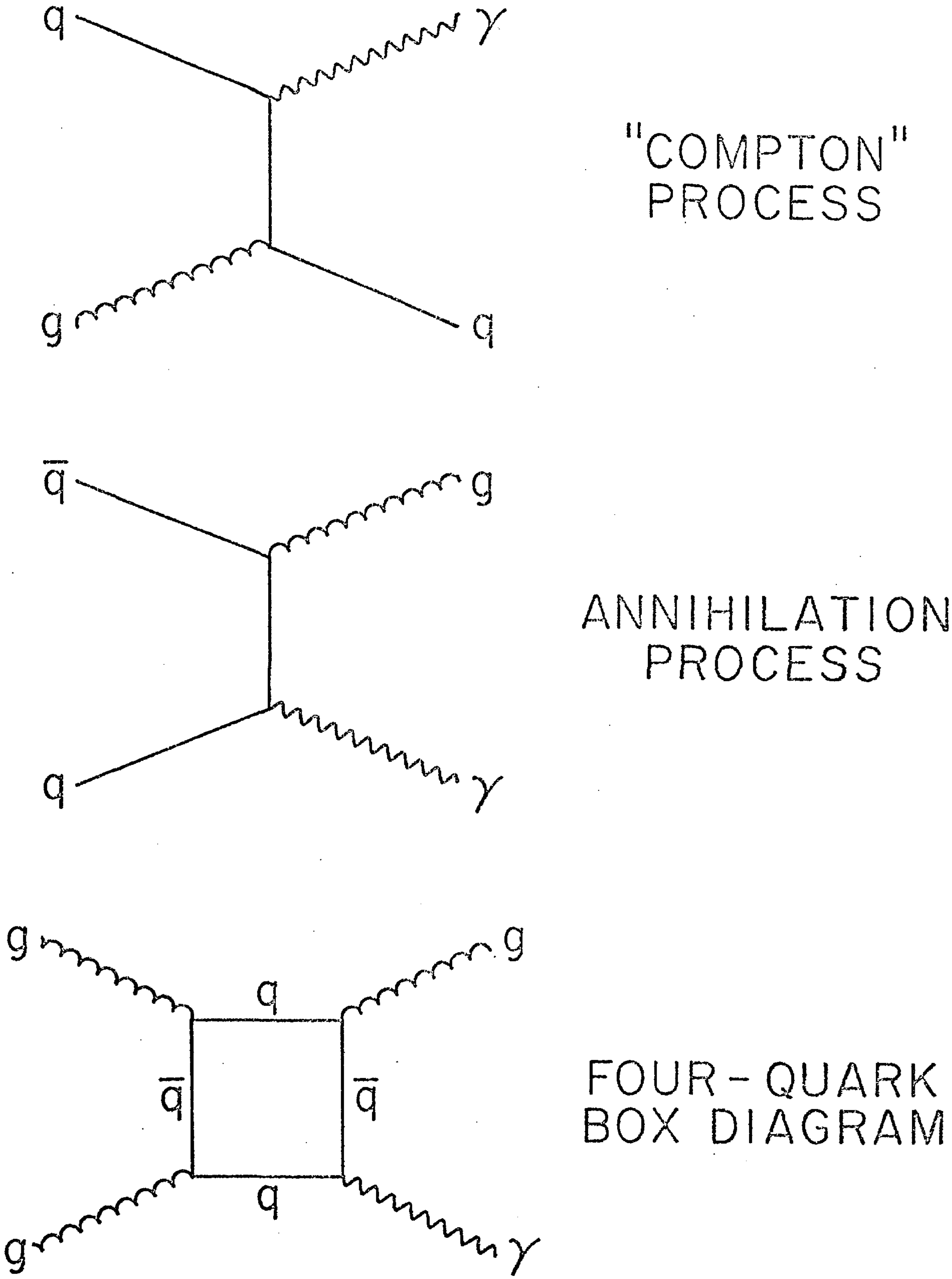
4. Elementary diagrams contributing to the production of two direct photons. The Drell-Yan diagram is shown for comparison purposes. (Permutations and exchange graphs for the indicated processes are not explicitly show.)

5. Schematic layout of our proposed experimental arrangement.

6. Enlarged schematic view of the target region indicating orientation of individual elements. Angle values denote strip orientations relative to 0° for a vertical strip (corresponding to readout of the horizontal coordinate).

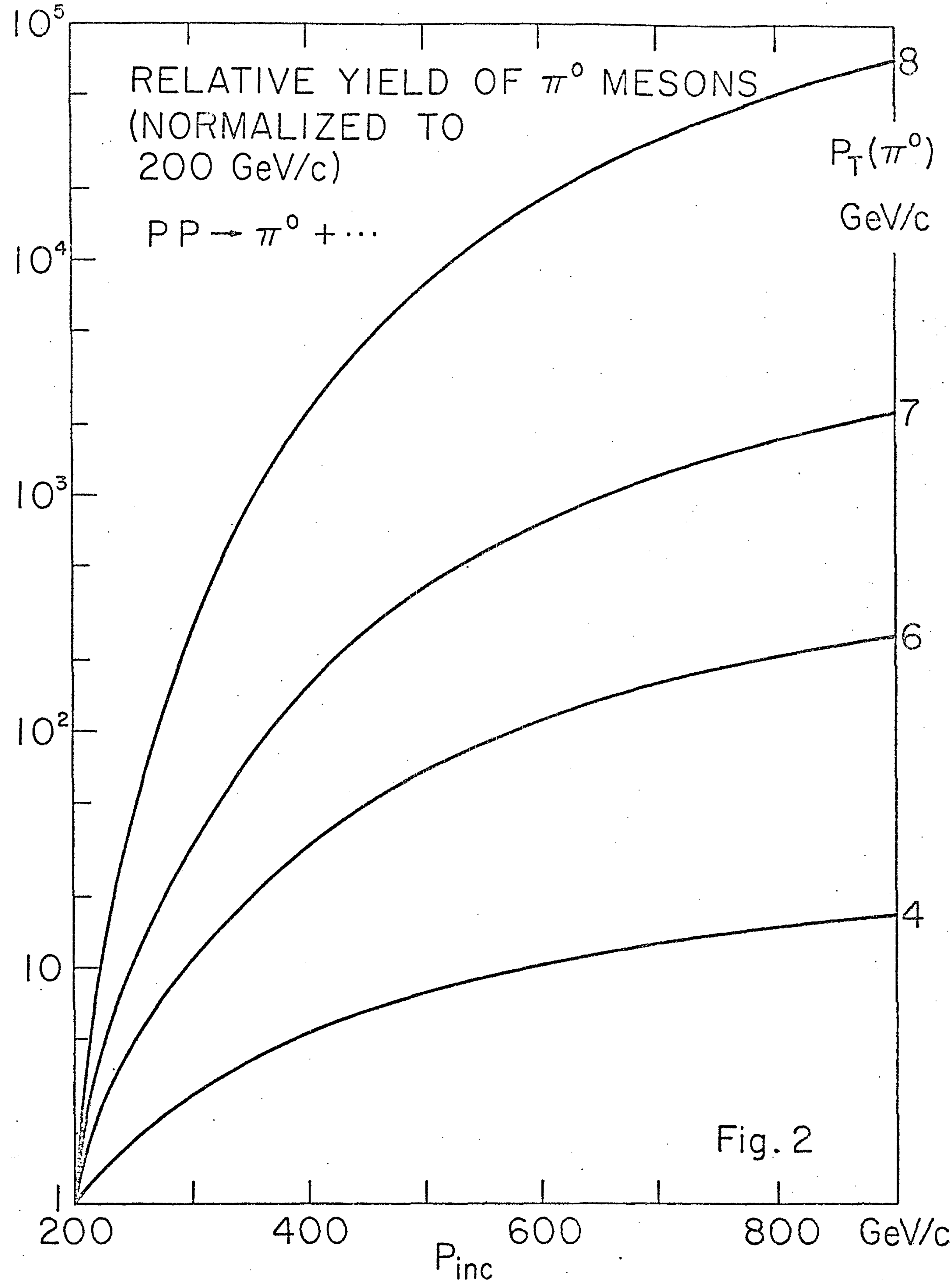
7. Enlarged schematic of downstream proportional system indicating orientations of individual chambers and their approximate dimensions. Angle values denote wire orientations relative to 0° for a vertical wire. Also shown is an enlarged view of the beam region for a representative set of 4 chambers. The numerical values indicate the level of residual redundancy in various spatial regions assuming completely desensitized strips.

8. General features of the proposed liquid argon calorimeter. Only the detector itself is depicted; the entire unit is to be enclosed within a cylindrical dewar (not shown). See text for further details.



q
γ
"COMPTON"
PROCESS
g
q
$\bar{q}$
g
ANNIHILATION
PROCESS
q
γ
g
g
q
$\bar{q}$
$\bar{q}$
FOUR-QUARK
BOX DIAGRAM
q
g
γ

Fig. 1



RELATIVE YIELD OF π^0 MESONS
(NORMALIZED TO
200 GeV/c)
$PP \rightarrow \pi^0 + \cdots$
10^5
10^4
10^3
10^2
10
1
200
400
600
800
GeV/c
P_{inc}
$P_T(\pi^0)$
GeV/c
8
7
6
4

Fig. 2

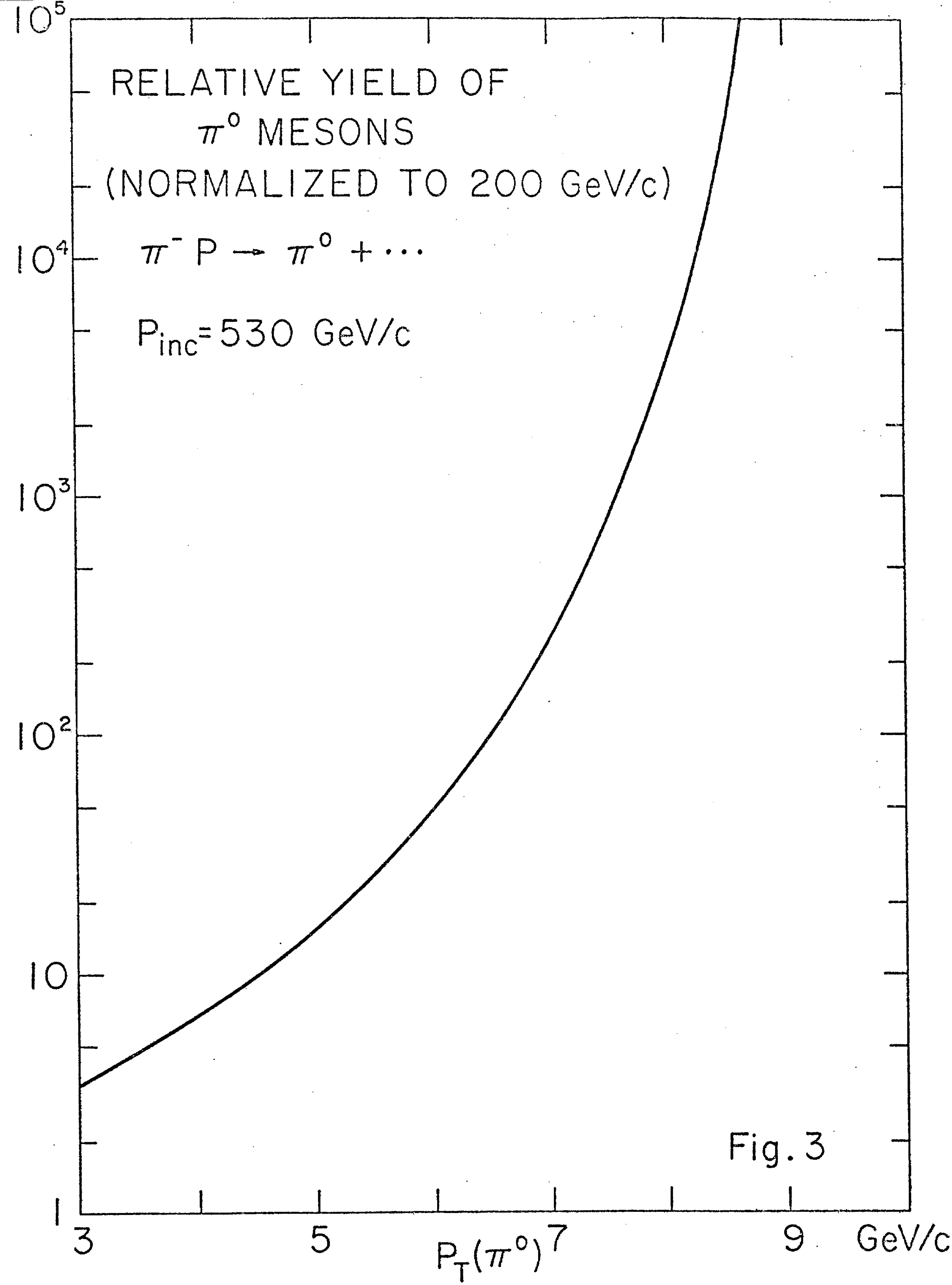
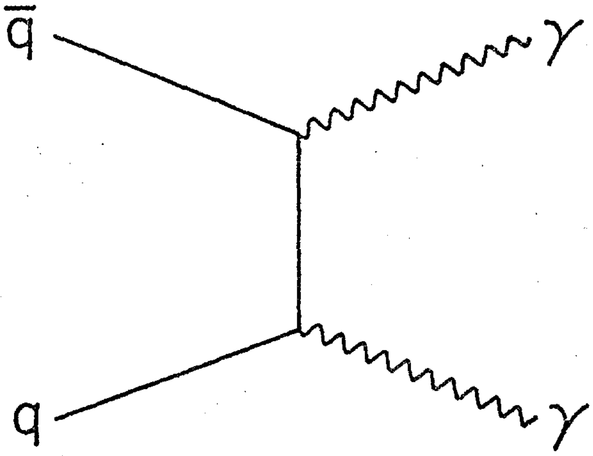
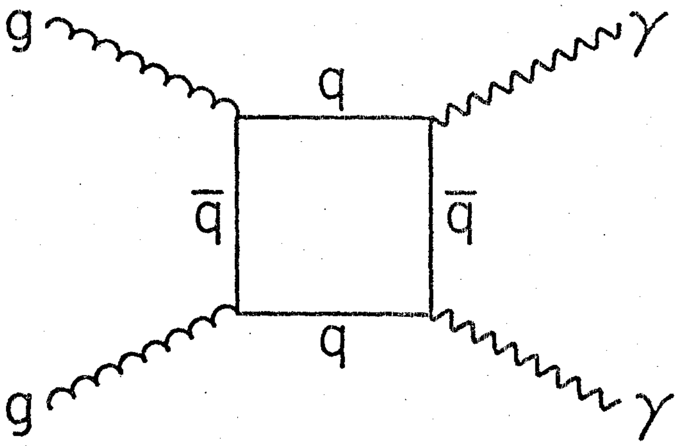

RELATIVE YIELD OF
π^0 MESONS
(NORMALIZED TO 200 GeV/c)
$\pi^- P \rightarrow \pi^0 + \cdots$
P_{inc}=530 GeV/c
10^5
10^4
10^3
10^2
10
1
3
5
7
9
GeV/c
$P_T(\pi^0)$

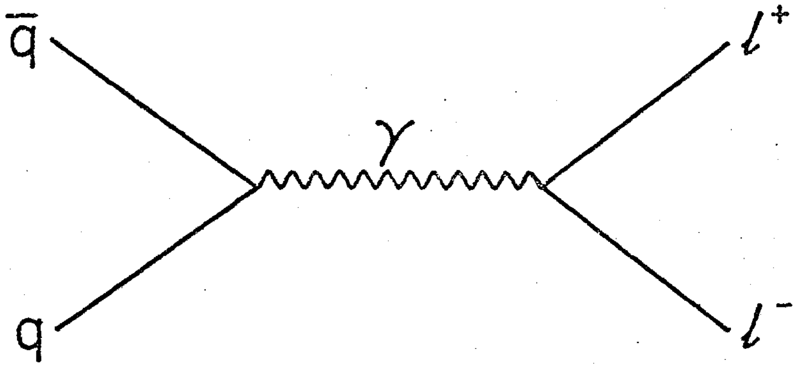
Fig. 3



ANNIHILATION
PROCESS

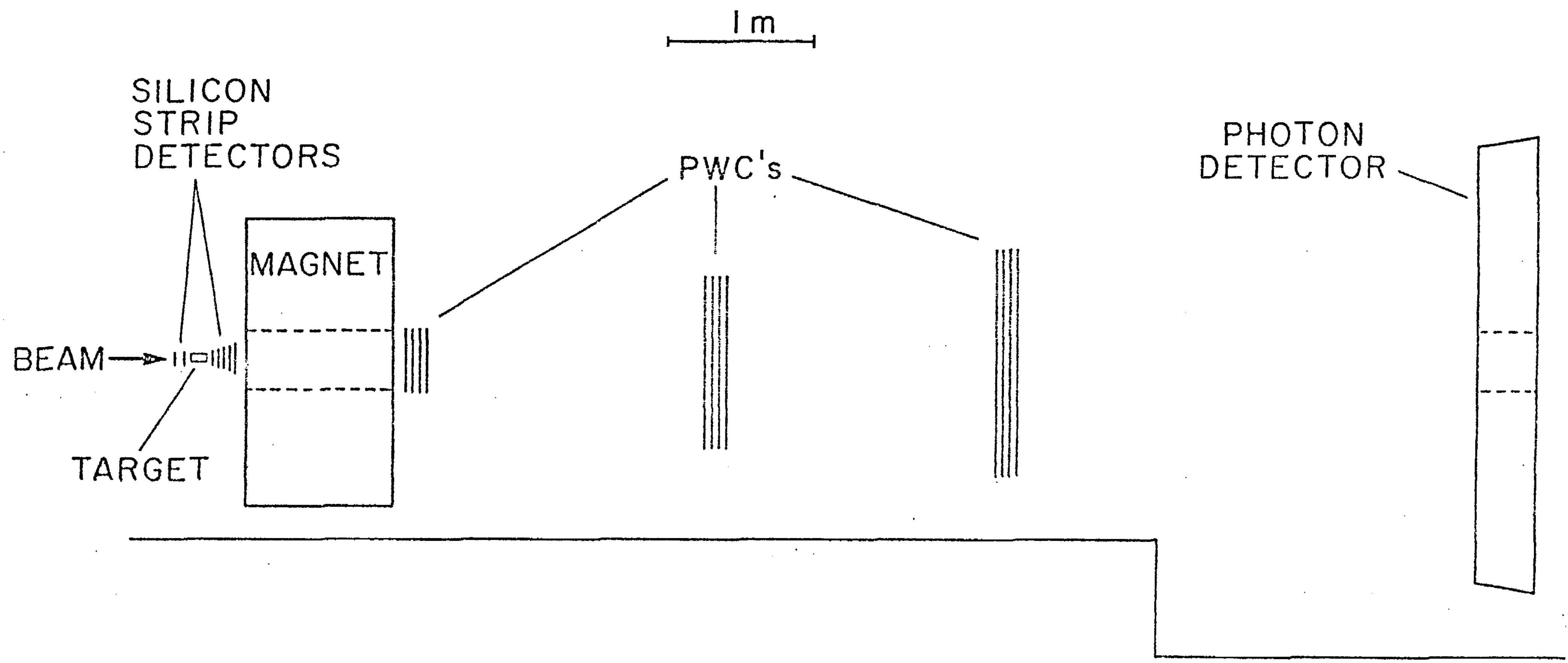


FOUR-QUARK
BOX DIAGRAM



DRELL-YAN
PROCESS

Fig. 4



EXPERIMENTAL LAYOUT

Fig. 5

DETAIL OF TARGET REGION

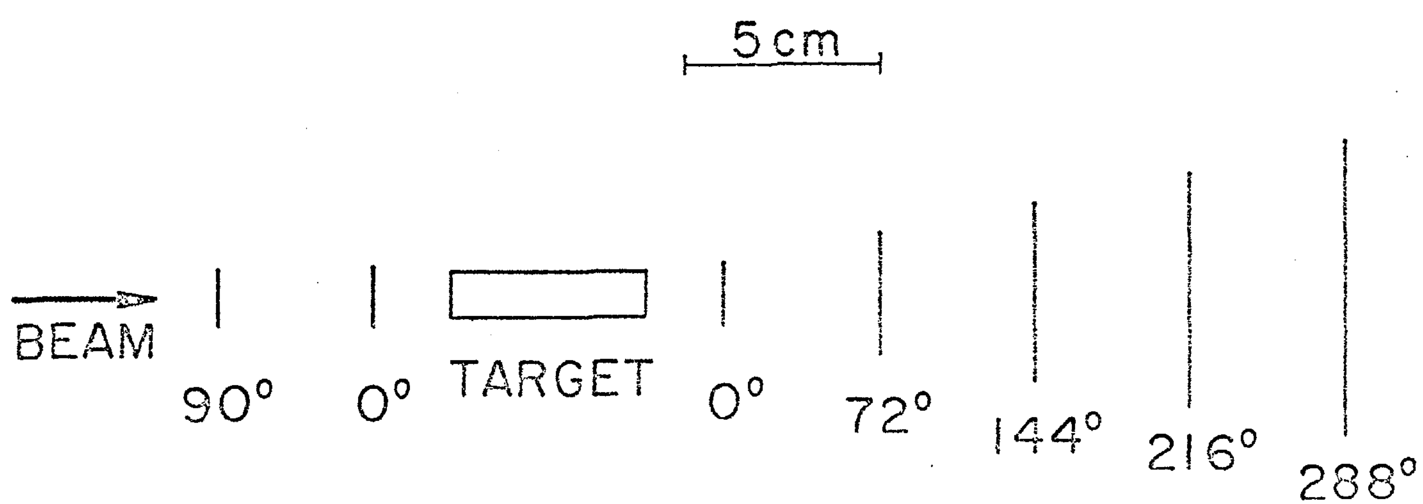


Fig. 6

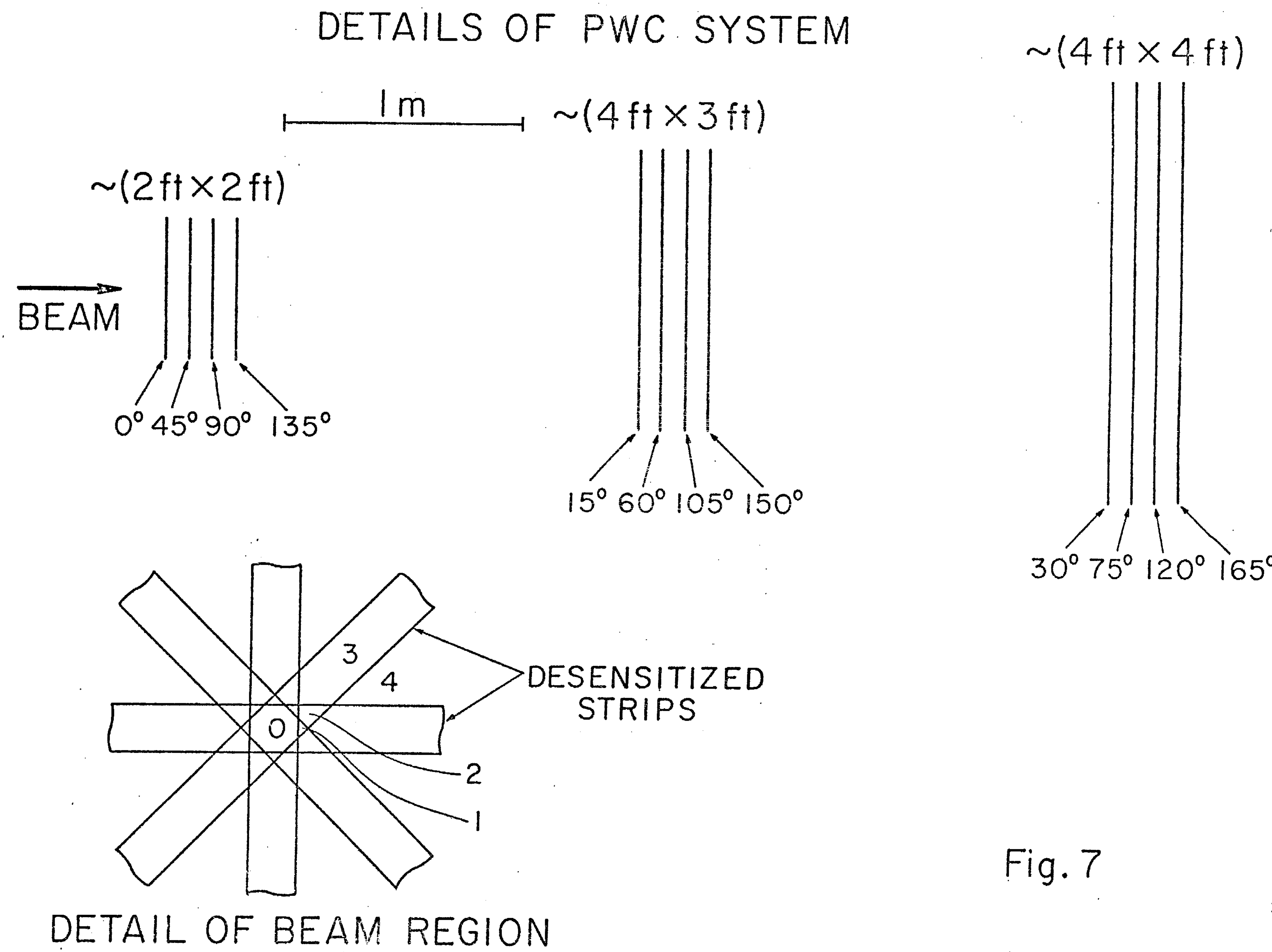

DETAILS OF PWC SYSTEM
1 m
BEAM
~(2 ft × 2 ft)
0° 45° 90° 135°
~(4 ft × 3 ft)
15° 60° 105° 150°
~(4 ft × 4 ft)
30° 75° 120° 165°
3
4
0
2
1
DESENSITIZED STRIPS
DETAIL OF BEAM REGION

Fig. 7

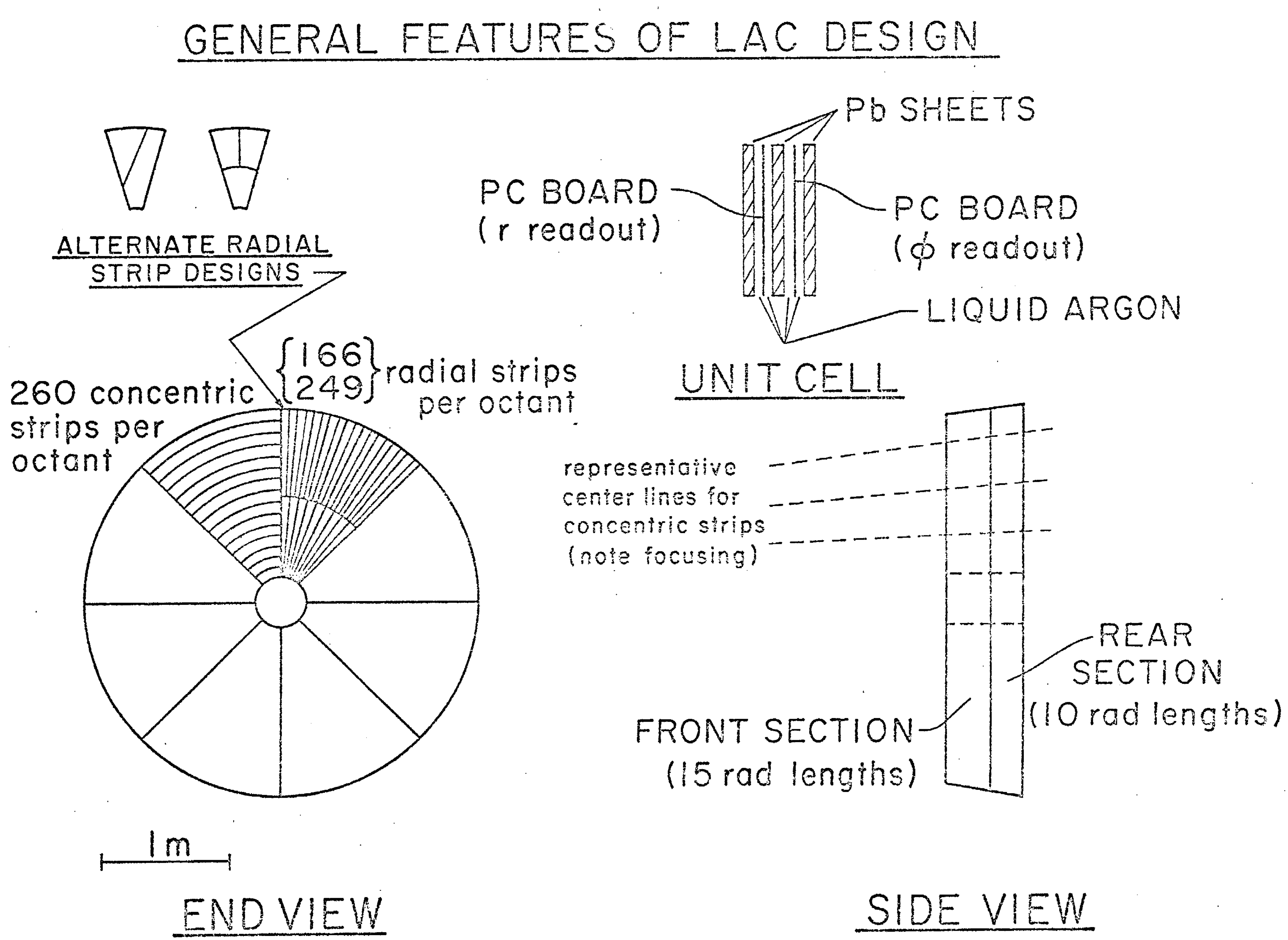

GENERAL FEATURES OF LAC DESIGN
ALTERNATE RADIAL STRIP DESIGNS
260 concentric strips per octant
{166 249} radial strips per octant
1m
END VIEW
PC BOARD (r readout)
Pb SHEETS
PC BOARD (φ readout)
LIQUID ARGON
UNIT CELL
representative center lines for concentric strips (note focusing)
REAR SECTION (10 rad lengths)
FRONT SECTION (15 rad lengths)
SIDE VIEW

Fig. 8